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GSMS: A Barrier Coverage Algorithm for Joint Surveillance Quality and Network Lifetime in WSNs

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ABSTRACT Barrier coverage problem is one of the most crucial issues in wireless sensor networks (WSNs) which have been applied to a wild range of applications. A lot of algorithms have been proposed to cope with this problem. However, the majority researches apply the Boolean Sensing Model (BSM) and the sensing frequency of the sensor is not considered, which are difficult to reflect the physical features of the sensing component. This paper proposed a barrier coverage algorithm, called Guaranteeing Surveillance Quality with Minimal Number of Active Sensors, or *GSMS* in short, aiming to guarantee the surveillance quality for a given monitoring region while activating the minimal number of active sensors. By applying the Probability Sensing Model (PSM) and considering sensing frequency, the proposed *GSMS* algorithm calculates the sensing probability of every location in the monitoring region and identifies the bottleneck location of surveillance quality. Then the *GSMS* algorithm prior schedules the sensor with the maximal contribution to the bottleneck location in terms of surveillance quality. The experimental study reveals that the proposed *GSMS* algorithm outperforms the existing algorithm in terms of the number of active sensors, lifetime of the WSNs, efficiency as well as the cooperative sensing probability.

INDEX TERMS Wireless sensor networks, barrier coverage, probability sensing model, surveillance quality, sensing frequency.

I. INTRODUCTION

Wireless Sensor Networks have been widely applied in various domains such as environment monitoring, hazardous area surveillance and intruder detection for its low cost, lightweight, advanced wireless communication technologies and so on [1]. The coverage problem is one of the important issues that draw a lot of attention in WSNs. Generally, the coverage problems can be classified into three main categories: target coverage, area coverage, and barrier coverage. The target coverage aims to monitor some specific objects while area coverage aims to monitor the entire region. The barrier coverage is different from them. It is mainly applied in the border surveillance application which aims to detect intruders passing through a given monitoring region. In literature, existing studies [2]–[4] proposed a number of barrier coverage mechanisms which aimed to find a set of sensors to form a defense line for detecting any possible crossing path [5]. Each independent defense line is called barrier which acts as an electric fence and detects the moving target.

Because the border features of geographical region, the monitoring region of barrier coverage is always considered as a long and irregular belt. The barrier coverage of WSNs is generally applied in very crucial or hazardous circumstance such as military and homeland security. It is necessary to ensure that the barrier should effectively surveil every crossing path and detect any intruder that infiltrates the sensing range. However, the sensing ability and the battery of the sensor are both limited. Therefore, most related works major concerned two issues: the surveillance quality and the lifetime of WSNs.

The surveillance quality generally depends on sensing ability of the sensor and the scheduling algorithm designed

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for constructing the barrier. The sensing ability is measured by sensing model which will directly influence the surveillance quality of the barrier. Most of the researches applied the Boolean Sensing Model (BSM) and aimed to guarantee that the constructed barrier has at least 1-barrier coverage in the monitoring region. However, the *BSM* assumed that the coverage range of each sensor is a perfect disc, which is difficult to reflect the physical features of sensing. On the contrary, the Probability Sensing Model (PSM) considers that the sensing ability of each sensor will be decreased with the distance between the sensor and the intruder and can be described by a decreasing function. Compared with the BSM, the PSM is much more practical because it can reflect the physical sensing behavior of most real sensors. In this paper, a novel barrier coverage algorithm is proposed based on PSM, aiming to guarantee the surveillance quality of the constructed barrier.

The other important goal is to prolong the lifetime of the WSNs. Since sensors are battery powered, it is an important challenge to maximize the lifetime of the WSNs under the constraint that a certain level of surveillance quality should be guaranteed. In literature, most researches were developed based on the assumption that the deployed sensors are battery-powered. To prolong the network lifetime, most of them aimed to construct several independent coverage sets of sensors. Sensors in different coverage sets can stay in active state in turn and all the other sensors stayed in sleeping state for prolonging the network lifetime. Since the number of sensor sets highly impact the network lifetime, the common goal of these studies aimed to reduce the number of sensors in each independent sensor set.

Based on the discussions mentioned above, this paper aims to propose a barrier coverage algorithm, called *GSMS*, which guarantees the required surveillance quality while maximizing the lifetime of WSNs based on the PSM. The main challenge is to construct a barrier which satisfies the required surveillance quality by using as few as possible active sensors. To overcome this challenge, the proposed *GSMS* algorithm firstly partitions the whole region into several equal-sized grids and then calculates the sensing probability of each grid in the monitoring region. Then *GSMS* aims to identify the bottleneck grids which provide the lowest surveillance quality. To improve the quality of these bottleneck grids, *GSMS* prior allocates the sensor with the maximal contribution to the bottleneck grids, aiming at minimizing the number of active sensors that participate in the defense barrier. Besides, the proposed *GSMS* algorithm takes the sensing frequency and speed of the intruder movement into consideration.

The main contributions of this paper are itemized as follows:

(1) **Considering physical sensing characteristics**. Most of the previous works applied BSM to develop barrier coverage mechanisms [6]–[8]. Since the estimations of coverage quality are not accurate, the constructed defense barrier might exist coverage holes in the actual applications. This paper applies the PSM to evaluate the surveillance quality which can refects the physical characteristics of sensors.

(2) **Considering the sensing frequency of the sensor.** Different from the existing researches [1], [9], the proposed *GMSM* algorithm takes into account the sensing frequency which can accurately schedule appropriate sensors to satisfy the required surveillance quality.

(3) **Adopting Bottleneck-first and maximal-contribution-first strategies.** The proposed *GSMS* algorithm identifies the bottleneck grid and prior allocates sensors with the maximum contribution to cover these grids. By collaborating with the two strategies, the number of active sensors that participate in the defense barrier can be significantly reduced, as compared with the existing researches [18], [20].

(4) **High utilization of sensors.** The proposed *GSMS* algorithm constructs the barrier by scheduling sensors from top to bottom and left to right of the monitoring region. This can increase sensor utilization and construct a larger number of distinct barriers.

(5) **Exploiting more opportunities for barrier construction.** The proposed *GSMS* algorithm adopts the backtracking mechanism to handle the failure situation when constructing the barrier. The backtracking mechanism further exploits more opportunities for barrier construction and hence the number of constructed defense barrier can be increased.

II. RELATED WORK

A large number of researches addressed the barrier coverage problem and proposed the algorithms in recent years. These algorithms can be categorized into two classes: BSM and PSM. The following reviews these researches and illustrates the contribution of this paper, as compared with the existing works.

A. BARRIER COVERAGE BY APPLYING BSM (BOOLEAN SENSING MODEL)

In literature, a lot of researches constructed defense barrier based on BSM which considers the sensors have perfect sensing range. That is, each sensor can detect any occurrence of an event if the event occurs in the sensing range of the sensor. Lai and Jiang [10] proposed an optimal node selection algorithm which applied the maximum-flow-and-minimum-cost approach to maximize the barrier coverage degree. The proposed algorithm used minimum numbers of detecting nodes and forwarding nodes to hold the sink-connect property. Khalifa *et al.* [11] proposed an algorithm to repair coverage holes using mobile sensor nodes. The participating nodes collaborated to approximate the area of the hole by considering a lot of parameters, including the coverage redundancy, residual energy, and moving distance, aiming to select a suitable replacement to cover the hole. Elhoseny *et al.* [12] proposed a new k-coverage model to extend a WSNs lifetime based on the genetic algorithm. The proposed method improved the WSNs's performance in terms of the amount of the consumed energy, the network lifetime and the required time to switch between different covers. Gupta *et al*. [13] proposed a probabilistic approach to determine whether or not a sensor in a heterogeneous WSN is redundant. Furthermore, they proposed a scheduling protocol to identify all the redundant sensors and scheduled them to sleep without creating any coverage hole in the field of interest so that the lifetime is increased.

Mostafaei *et al*. [14] devised an imperialist competitive algorithm-based method to solve the barrier coverage problem. They proposed an algorithm to find the best sensor nodes to cover the network barriers in the deployed network. The proposed approach used an imperialist competitive algorithm to select the best sensor nodes to cover barrier paths. Han *et al*. [15] analyzed the characteristics of four recent energy-efficient coverage strategies by carefully choosing four representative connected coverage algorithms. Then comparison in terms of network lifetime, coverage time, average energy consumption and ratio of dead nodes is given.

Kong *et al*. [16] proposed a software-defined system consisting of the cloud-based architecture and the barrier maintenance algorithm. The cloud-based architecture provided high computation capability and a global view. The proposed algorithm imitated an elastic band, which continuously retains the barrier coverage wrapping the dynamic zone. This system approaches the maximum number of barriers for high monitoring quality Chang *et al*. [18] proposed a decentralized scheme. The proposed scheme constructs a defense barrier from left to right of the region based on the contributions of the sensors to the coverage. The proposed mechanism constructed a maximal number of disjoint sets of sensors, such that each set was composed of the minimum number of sensors. Mostafaei and Meybodi [19] proposed an energy-aware scheduling method based on learning automata. Each node is equipped with learning automation to select the best node to guarantee barrier coverage, at any given time. Weng *et al*. [20] addressed the issue of how to construct a defense barrier by organizing a set of sensors for detecting the intruders. They firstly proposed a novel graph model, called CA-net. Based on the CA-net, an efficient k-barrier construction decentralized mechanism, called *BCA*, is proposed aiming to construct a maximum number of distinct k-barriers. All these literatures mentioned above adopted the BSM and aimed to guarantee the k-barrier or prolong the lifetime of WSNs on the condition of k-barrier. The BSM is relatively simple to analyze the surveillance quality of barrier. However, it cannot reflect the physical characteristics of the sensors. The performance demonstrated in these literatures may not be accurate enough in the real applications.

B. BARRIER COVERAGE BY APPLYING PSM (PROBABILITY SENSING MODEL)

Different from BSM, the PSM considers that the sensing ability decreases with the distance between the sensor and the location of occurrence of an event. The PSM is more practical since it reflects the physical characteristics of the sensor, as compared with BSM [21]. Zhuang *et al*. [17] aimed to design an efficient algorithm for complex conditions that can combine the compound event confidence. A multiplier method based on an active-set strategy was proposed to optimize the multiple constraints in compound event barrier coverage. The algorithm calculated the coverage ratio efficiently and allocated the sensor resources reasonably in compound event barrier coverage. Zhang *et al*. [22] proposed an iterative scheme aimed to provide strong barrier coverage under the probabilistic sensing model. The proposed scheme aimed to minimize the number of active sensors. It considered both target detection probability and system false alarm probability and hence provided a more practical solution for barrier coverage. Dong *et al*. [23] considered the solar-powered sensor and allowed the battery to be recharged for maintaining the perpetual lifetime of sensor networks. They proposed a barrier coverage mechanism, called *MSQ*, which aimed to maximize the surveillance quality of a given boundary curve by appropriately scheduling a set of solar-powered sensors.

Si *et al*. [24] applied the exponential decay probabilistic sensing model for directional sensor networks. Besides, they proposed a fault-tolerant probabilistic sensing model for handling orientation error and rotation error. Furthermore, a hybrid probabilistic sensing model is formed by combining the exponential decay probability with the fault-tolerant probability. Akbarzadeh *et al*. [25] focused on optimizing the sensor placement problem and devised an original probabilistic sensing model for sensors. This new model considered more parameters, including sensing range and sensing angle. Furthermore, the sensing capacity probability and critical environmental factors such as terrain topography are taken into consideration.

Although the studies mentioned above applied the PSM, these solutions [17], [22]–[25] are centralized and the sensing frequency of the sensor did not be considered.

Table 1. gives a comparison of the main characteristics of the proposed *GSMS* and the existing related works.

By applying the Probability Sensing Model (PSM) and considering sensing frequency, the proposed *GSMS* algorithm aims to construct a barrier which uses the minimal number of active sensors but guarantees the required surveillance quality.

III. ASSUMPTIONS AND PROBLEM STATEMENT

A. NETWORK MODEL

The considered monitoring area is a rectangle region R with size $L \times W$, where L and Z are the length and width of R, respectively. Assume that a set of n sensors $S = \{S_1, S_2, \ldots, S_n\}$ are randomly deployed in R. Each sensor s_i has a unique ID and its geographical coordinates are represented by (x_i, y_i). Assume that each sensor is aware of its location and the boundaries of R. Let r_s and r_c denote the sensing radius and communication radius of each sensor, where $r_s \geq 2r_c$.

TABLE 1. **Comparison of the main characteristics of the proposed *GSMS* with the existing related works.**

Related Work	Physical Characteristics of Sensor	Surveillance Quality	Grid-Based Model	Sensing Frequency	Extend Lifetime	Centralized / Decentralized
[10]	×	✓	×	×	✓	Centralized
[11]	×	✓	×	×	✓	Centralized
[12]	×	×	×	×	✓	Centralized
[13]	×	×	×	×	✓	Centralized
[14]	×	✓	×	×	×	Centralized
[15]	×	✓	×	×	✓	Centralized
[16]	×	✓	×	×	×	Centralized
[17]	✓	✓	×	×	×	Centralized
[18]	×	✓	✓	×	✓	Decentralized
[19]	×	✓	×	×	✓	Centralized
[20]	×	✓	✓	×	✓	Decentralized
[22]	✓	✓	×	×	✓	Centralized
[23]	✓	✓	×	×	✓	Centralized
[24]	✓	✓	×	×	×	Centralized
[25]	✓	✓	×	×	×	Centralized
Ours	✓	✓	✓	✓	✓	Decentralized

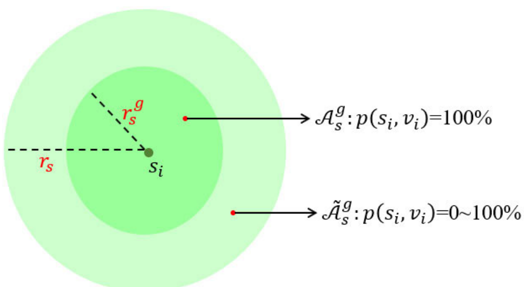


FIGURE 1. **The logic view of the probability sensing model.**

B. SENSING MODEL

Fig. 1 depicts the probability sensing model [1] adopted in this paper. The sensing range of each sensor can be divided into two different regions. The inner region is the guaranteed sensing range denoted by $\mathcal{A}_s^g$ with radius r_s^g while the outer region is the probability sensing range denoted by $\tilde{\mathcal{A}}_s^g$ with radius r_s. In case that the event occurred at location v_i in the $\mathcal{A}_s^g$, the detection probability of sensor s_i is 100%. However, if the event occurred at location v_i which is located in $\tilde{\mathcal{A}}_s^g$, the detection probability is ranging from 0% to 100%, depending on the distance between the sensor s_i and point v_i.

Let (x_{v_i}, y_{v_i}) denote the coordinates of the point v_i located in the sensing range of s_i. Let $p(s_i, v_i)$ and $d(s_i, v_i)$ denote the sensing probability that sensor s_i detects an event occurred at a point v_i and the distance between the sensor s_i and point v_i, respectively. The value of $p(s_i, v_i)$ can be calculated by the following Exp. (1).

$$p(s_i, v_i) = \begin{cases} 1 & d(s_i, v_i) \le r_s^g \\ e^{-\lambda\left(d(s_i,v_i)-r_s^g\right)^{\gamma}} & r_s^g < d(s_i, v_i) < r_s \\ 0 & d(s_i, v_i) \ge r_s \end{cases} \quad (1)$$

where λ and γ represent the path loss exponents of the sensing signal strength of the sensor and both two parameters can be adjusted with the physical properties of the sensor. The distance $d(s_j, v_i)$ in Exp. (1) can be obtained by the following expression.

$$d(s_i, v_i) = \sqrt{\left(x_i - x_{v_i}\right)^2 - \left(y_i - y_{v_i}\right)^2} \quad (2)$$

C. PROBLEM STATEMENT

This paper considers the barrier coverage problem for a given WSN, aiming to construct a barrier by scheduling a minimal number of working sensors such that the predefined surveillance quality can be guaranteed. The following presents the objective function and the constraints for constructing the barrier.

Let ζ denote a possible scheduling algorithm which aims to take S and R as inputs and determine a set of connected active sensors $S^{act} = \{s_1^{act}, s_2^{act}, \ldots, s_n^{act}\}$, where $S^{act} \subseteq S$, for constructing the barrier, denoted by DB_ζ, in monitoring region R. A crossing path is said to be valid if it passes through the complete width of the monitoring region. Let $\mathfrak{p}$ denote the set of all possible valid crossing paths. Fig. 2 gives an example for illustrating the constructed DB_ζ and the valid crossing paths. As shown in Fig. 2, the constructed DB_ζ is a defense barrier for detecting the intruder in R. In this example, η_1 and η_2 are valid crossing paths while η_1' and η_2' are invalid ones.

Consider a valid crossing path η along which an intruder passes through k active sensors s_1^η, $s_2^\eta, \ldots, s_k^\eta$. Let the intruder be detected by sensor s_i^η at ρ_i sensing locations loc_1^i, $loc_2^i, \ldots, loc_{\rho_i}^i$ when considering the sensing frequency and the speed of intruder. Let notation q_η denote the surveillance quality of defense barrier to the crossing path η. Exp. (3)

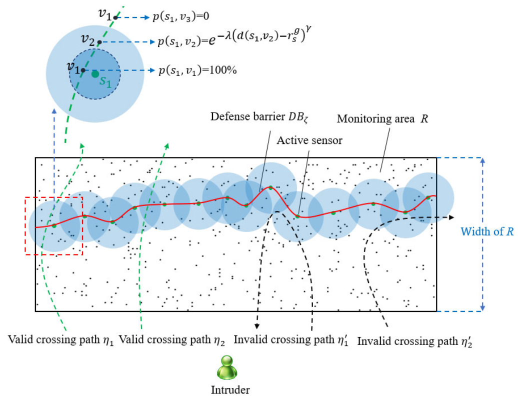


FIGURE 2. An example of the defense barrier.

evaluates the surveillance quality q_η.

$$q_\eta = \sum_{i=1}^{k} \sum_{j=1}^{\rho_i} p\left(s_i^\eta, loc_j^i\right) \tag{3}$$

The following defines the surveillance quality of a constructed barrier.

Definition: Surveillance quality of DB_ζ

Given a scheduling algorithm ζ which constructs a barrier DB_ζ, the surveillance quality, denoted by q^{DB_ζ}, is the weakest surveillance quality of DB_ζ to all the possible crossing paths. That is

$$q^{DB_\zeta} = \min_{\forall\eta\in\mathfrak{p}} q_\eta \tag{4}$$

For a given constructed defense barrier DB_ζ, let notation $x_{i,\zeta}$ be the Boolean value indicating whether sensor s_i participates in the DB_ζ. That is,

$$x_{i,\zeta} = \begin{cases} 1, & \text{if } s_i \in DB_\zeta \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

Let σ denote the number of active sensors which are scheduled for performing the monitoring task. The number of active sensors that participate in DB_ζ can be formulated by Exp. (6)

$$\sigma = \sum_{\forall s_i \in S} x_{i,\zeta} \tag{6}$$

This paper aims to minimize the number of active sensors that participate in the defense barrier while guaranteed the surveillance quality. Exp. (7) gives the objection function of this paper.

Objective Function:

$$\boldsymbol{Minimize}(\sigma) \tag{7}$$

When designing the algorithm that achieves Exp. (7), some constraints listed below should be satisfied. The following presents the constraints.

The first constraint is surveillance quality constraint which requires the constructed barrier to guarantee the user predefined surveillance quality. Let q_{req} denote the predefined surveillance quality. Exp. (8) shows the surveillance quality constraint.

1) SURVEILLANCE QUALITY CONSTRAINT

$$q_{DB_\zeta} \geq q_{req} \tag{8}$$

There are two states for each sensor: the active and sleeping states. Let Boolean variable M_i^{sen} and M_i^{slp} represent that sensor $s_i \in S$ stays in active or sleeping states, respectively. That is

$$M_i^{sen} = \begin{cases} 1, & \text{if } s_i \text{ stays in active state} \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

$$M_i^{slp} = \begin{cases} 1, & \text{if } s_i \text{ stays in sleeping state} \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

The sensor state constraint reflects the limitation that each sensor can stay in either active state or sleeping state at any given time point.

2) SENSOR STATE CONSTRAINT

$$M_i^{sen} + M_i^{slp} = 1 \tag{11}$$

To achieve the objective function as shown in Exp. (7), the minimal requirement for the constructed barrier is 'no hole'. That is, the constructed barrier should satisfy the constraint that the set of active sensors whose sensing ranges can form a continuous barrier without containing any coverage hole. Let $\mathcal{A}_i$ denote the sensing range of the sensor s_i. The following constraint shows that there always exists a sensing overlapping area between any two neighboring sensors in the constructed DB_ζ.

3) CONTINUOUS CONSTRAINT

$$\mathcal{A}_i \cap \mathcal{A}_{i+1} \neq \emptyset, \quad \forall s_i \in DB_\zeta \tag{12}$$

Another important property that should be satisfied for a barrier is the boundary constraint. Let $s_{leftmost}$ and $s_{rightmost}$ denote the leftmost and rightmost sensors of the constructed DB_ζ, respectively. Let B_{left} and B_{right} denote the left and right boundaries of R, respectively. The *boundary constraint* requires that the coverages of $s_{leftmost}$ and $s_{rightmost}$ should be overlapped with the left and right boundaries, respectively. The following presents the boundary constraint.

4) BOUNDARY CONSTRAINT

$$\mathcal{A}_{leftmost} \cap B_{left} \neq \emptyset \wedge \mathcal{A}_{rightmost} \cap B_{right} \neq \emptyset,$$

where

$$s_{leftmost}, s_{rightmost} \in DB_\zeta \tag{13}$$

The following section will present the proposed algorithm which aims to achieve the objective function depicted in Exp. (7) while satisfying the constraints given in Exps. (8), (11), (12) and (13).

IV. THE PROPOSED SCHEDULING ALGORITHM

Given a user predefined surveillance quality q_{req}, this paper aims to design a barrier construction algorithm which aims to schedule the minimal number of sensors to form a defense barrier which guarantees the surveillance quality q_{req}. The proposed algorithm mainly consists of three phases: *Space Partitioning Phase*, *Sensing Probability Calculation Phase* as well as *Scheduling and Barrier Construction Phase*. The *Space Partitioning Phase* aims to partition the monitoring region into some grids such that the computational complexity can be reduced. The *Sensing Probability Calculation Phase* aims to calculate the sensing probability of each grid. Finally, the *Scheduling and Barrier Construction Phase* aims to construct a defense barrier by repeatedly performing the following three steps until the barrier has been completely constructed. The first step is to extend the constructed barrier and the second step is to identify the bottleneck grids of the extended barrier. Finally, the third step further schedules the sensors which have the maximal contribution to the bottleneck grids to stay in active state. The following presents the details of each phase.

A. SPACE PARTITIONING PHASE

The main concept of this paper is to identify the bottleneck of the constructed barrier and improve the bottleneck in terms of surveillance quality. The bottleneck surveillance quality of the constructed barrier will be identified by evaluating the surveillance quality of each possible valid crossing paths. However, there is an infinite number of points on the constructed barrier so that the possible valid crossing paths are uncountable. To simplify the investigated issue and to reduce the computational complexity, the grid-based method is applied. This phase firstly partitions the monitoring region into several equal-sized grids. The crossing path will be transformed into the grid-based crossing path. The surveillance quality will be calculated for each grid that is covered by sensors $s_i \in DB_{GSMS}$. We consider that all points in a grid have the same surveillance quality. Each grid will be labeled with two-dimensional coordinates. The most top-left grid in R is labeled with $(1, 1)$. The x-coordinate and y-coordinate are increased by one if the location of a grid shifts one position toward the right and down directions, respectively. Let $g_{(x,y)}$ denote the grid with coordinates (x, y). Fig. 3 shows an example of partitioned monitoring region R and two crossing paths η_1 and η_2. The monitoring region R is partitioned into 16×10 equal-sized grids. The sensors s_1, s_2 and s_3 are active and participate in the defense barrier.

B. SENSING PROBABILITY CALCULATION PHASE

The main task of *sensing probability calculation phase* is to calculate the sensing probability of each grid that is covered by the sensors. As shown in Fig. 3, sensor s_1 is an active sensor that participates in the given defense barrier and its sensing range covers some grids in R.

Assume that sensor s_i covers grid $g_{(x,y)}$. The calculation of sensing probability depends on the situation whether or not

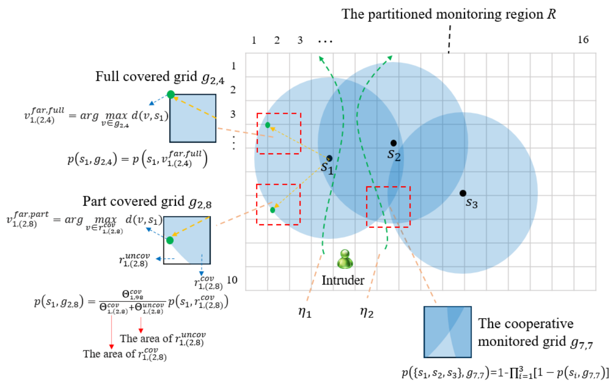


FIGURE 3. The partitioned monitoring region R and grid-based crossing paths.

the grid is fully covered by sensor s_i. Let $p\left(s_i, g_{(x,y)}\right)$ denote the sensing probability of grid $g_{(x,y)}$ detected by sensor s_i. Let $v_{i,(x,y)}^{far,full}$ denote the farthest point in grid $g_{(x,y)}$ to sensor s_i. That is,

$$v_{i,(x,y)}^{far,full} = arg \max_{v \in g(x,y)} d(v, s_i)$$

Point $v_{i,(x,y)}^{far,full}$ can be the representation point of all points of grid $g_{(x,y)}$. Therefore, the sensing probability of grid $g_{(x,y)}$ detected by sensor s_i can be measured by the sensing probability of the farthest point in $g_{(x,y)}$ detected by sensor s_i. That is,

$$p\left(s_i, g_{(x,y)}\right) = p\left(s_i, v_{i,(x,y)}^{far,full}\right) \tag{14}$$

On the other hand, if the grid $g_{(x,y)}$ is only partially covered by sensor s_i, the calculation of $p\left(s_i, g_{(x,y)}\right)$ is different from that of the full coverage case. Let $\mathfrak{r}_{i,(x,y)}^{cov}$ and $\mathfrak{r}_{i,(x,y)}^{uncov}$ denote the regions of $g_{(x,y)}$ that are covered and uncovered by sensor s_i, respectively. Let $v_{i,(x,y)}^{far,part} \in \mathfrak{r}_{i,(x,y)}^{cov}$ denote the farthest point in $\mathfrak{r}_{i,(x,y)}^{cov}$ to sensor s_i. That is,

$$v_{i,(x,y)}^{far,part} = \arg \max_{v \in \mathfrak{r}_{i,(x,y)}^{cov}} d(v, s_i)$$

The sensing probability of all points in $\mathfrak{r}_{i,(x,y)}^{cov}$ are also considered to be identical. The farthest point $v_{i,(x,y)}^{far,part}$ will be selected as the representing point of $\mathfrak{r}_{i,(x,y)}^{cov}$. Let $p\left(s_i, \mathfrak{r}_{i,(x,y)}^{cov}\right)$ denote the sensing probability of covered region $\mathfrak{r}_{i,(x,y)}^{cov}$ detected by sensor s_i. The value of $p\left(s_i, \mathfrak{r}_{i,(x,y)}^{cov}\right)$ can be measured by Exp. (15).

$$p\left(s_i, \mathfrak{r}_{i,(x,y)}^{cov}\right) = p\left(s_i, v_{i,(x,y)}^{far,part}\right) \tag{15}$$

It is obvious that the sensing probability of region $\mathfrak{r}_{i,(x,y)}^{uncov}$ detected by sensor s_i is 0. Let $\Theta_{i,(x,y)}^{cov}$ and $\Theta_{i,(x,y)}^{uncov}$ denote the area sizes of $\mathfrak{r}_{i,(x,y)}^{cov}$ and $\mathfrak{r}_{i,(x,y)}^{uncov}$, respectively. The value of $p\left(s_i, g_{(x,y)}\right)$ can be measured by applying Exp. (16).

$$p\left(s_i, g_{(x,y)}\right) = \frac{\Theta_{i,(x,y)}^{cov}}{\Theta_{i,(x,y)}^{cov} + \Theta_{i,(x,y)}^{uncov}} p\left(s_i, \mathfrak{r}_{i,(x,y)}^{cov}\right) \tag{16}$$

It is possible that more than one active sensors cover grid $g_{(x,y)}$ simultaneously. Let $\Phi_{(x,y)} = \{\tilde{s}_1, \tilde{s}_2, \ldots, \tilde{s}_u\}$ denote the set of active sensors that cover grid $g_{(x,y)}$. Let $p\left(\Phi_{(x,y)}, g_{(x,y)}\right)$ denote the cooperative sensing probability of grid $g_{(x,y)}$ detected by sensors $\tilde{s}_i \in \Phi_{(x,y)}$. The value of $p\left(\Phi_{(x,y)}, g_{(x,y)}\right)$ can be obtained by applying Exp. (17)

$$p\left(\Phi_{(x,y)}, g_{(x,y)}\right) = 1 - \prod_{\tilde{s}_i \in \Phi_{(x,y)}} \left[1 - p\left(\tilde{s}_i, g_{(x,y)}\right)\right] \quad (17)$$

As shown in Fig. 3, grid $g_{(2,4)}$ is fully covered by sensor s_1, the calculation of sensing probability of grid $g_{(2,4)}$ detected by sensor s_1 depends on the distance between the farthest point in $g_{(2,4)}$ and the location of sensor s_1.

The probability sensing model presented in Exp. (1) will be applied for calculating $p\left(s_1, g_{(2,4)}\right)$. That is

$$\begin{aligned} p\left(s_1, g_{(2,4)}\right) &= p\left(s_1, v_{1,(2,4)}^{far,full}\right) \\ &= \begin{cases} 1 & d\left(s_1, v_{1,(2,4)}^{far,full}\right) \le r_s^g \\ e^{-\lambda\left(d\left(s_1, v_{1,(2,4)}^{far,full}\right) - r_s^g\right)^\gamma} & r_s^g < d\left(s_1, v_{1,(2,4)}^{far,full}\right) < r_s \\ 0 & d\left(s_1, v_{1,(2,4)}^{far,full}\right) \ge r_s \end{cases} \end{aligned}$$

The grid $g_{(2,8)}$ is partially covered by sensor s_1. We have

$$\begin{aligned} p\left(s_1, r_{1,(2,8)}^{cov}\right) &= p\left(s_1, v_{1,(2,8)}^{far,part}\right) \\ &= \begin{cases} 1 & d\left(s_1, v_{1,(2,8)}^{far,part}\right) \le r_s^g \\ e^{-\lambda\left(d\left(s_1, v_{1,(2,8)}^{far,part}\right) - r_s^g\right)^\gamma} & r_s^g < d\left(s_1, v_{1,(2,8)}^{far,part}\right) < r_s \\ 0 & d\left(s_1, v_{1,(2,8)}^{far,part}\right) \ge r_s \end{cases} \end{aligned}$$

The sensing probability of grid $g_{(2,8)}$ detected by sensor s_1 is

$$p\left(s_1, g_{(2,8)}\right) = \frac{\Theta_{1,(2,8)}^{cov}}{\Theta_{1,(2,8)}^{cov} + \Theta_{1,(2,8)}^{uncov}} p\left(s_1, r_{1,(2,8)}^{cov}\right)$$

Furthermore, the grid $g_{(7,7)}$ is covered by sensors s_1, s_2 and s_3 simutaneously. That is, we have

$$\Phi_{(7,7)} = \{s_1, s_2, s_3\}$$

The cooperative sensing probability of grid $g_{(7,7)}$ detected by $\Phi_{(7,7)}$ is

$$p\left(\Phi_{(7,7)}, g_{7,7}\right) = 1 - \prod_{i=1}^{3} \left[1 - p\left(s_i, g_{7,7}\right)\right]$$

In this phase, the sensing probability of grid $g_{(x,y)}$ detected by active sensors should be calculated for those grids which are covered by one or more active sensors. In the next phase, the sensing probability of each grid can be used to measure the surveillance quality of the defense barrier to each valid crossing path.

C. SCHEDULING AND BARRIER CONSTRUCTION PHASE

This phase aims to schedule a set of appropriate active sensors to construct a defense barrier such that the number of active sensors can be minimized while the user predefined surveillance quality of the defense barrier can be guaranteed. The main idea of the proposed *GSMS* algorithm is to select the sensor with the maximal defense length to construct the basic defense barrier. Then the proposed algorithm schedules the appropriate sensors to improve the surveillance quality if the surveillance quality is not satisfied. In the conceptual level, the *GSMS* algorithm initially selects the first senor which is located in the most upper left location and satisfies the boundary constraint. After that, the proposed *GSMS* explores the sensor with the maximal contribution to the defense length and adds a new sensing range for constructing the barrier. Meanwhile, the *GSMS* algorithm identifies the weakest surveillance quality of the newly added sensing range. If the weakest surveillance quality cannot meet the requirement of user predefined surveillance quality, the *GSMS* algorithm will prior select the sensors with the largest contribution to strengthen the surveillance quality of that grid. This phase should be repeatedly executed to extend the defense barrier until the right boundary is reached.

As mentioned above, the barrier construction phase mainly consists of three tasks. The first task is to find the best sensor to form a new monitoring region for constructing and extending the uncompleted defense barrier. The second task is to identify the bottleneck grids in the newly added monitoring region. The final task is to improve the surveillance quality of the bottleneck grids by scheduling the minimal number of sensors to participate in the barrier construction. The detail of each task is presented as follow.

1) TASK I. BARRIER EXTENDING

Herein, we notice that the barrier is constructed by extending an additional segment step by step. The barrier extending process will be repeatedly performed from the left boundary and will be finished when the right boundary is reached by the constructed barrier. The goal of this task is to select one best sensor to extend the current barrier. To construct a defense barrier, the first sensor that participates in this barrier should be initially selected. Let s_{first} denote the first sensor that participates in the defense barrier. Since the *GSMS* algorithm expects to construct the defense barrier from top to bottom so that the deployed sensors can be fully utilized, the sensor located in the most upper left position of the monitoring region R and overlap with the left boundary will be selected as the s_{first}.

Let *DM* denote the *Decision Maker* which is responsible for exploring the new sensor to participate in the defense barrier. Let notations s_{DM}^{pre}, s_{DM}^{curr} and s_{DM}^{next} denote the previous, current and next decision makers, respectively. The main goal of this task is to select one sensor to play the role of s_{DM}^{next} such that the current barrier can be extended. To achieve this, the s_{first} will initially play the role of the first s_{DM}^{curr}.

Let S^{sleep} denote the set of sleeping (unscheduled) sensors and $S^{next}_{DM,candidate}$ denote the set of candidate sensors which satisfy Exp. (18).

$$S^{next}_{DM,candidate} = \left\{ s_i \,|\, \mathcal{A}_{s_i} \cap \mathcal{A}_{s^{curr}_{DM}} \neq \emptyset, \forall s_i \in S^{sleep} \right\} \tag{18}$$

That is, the sensor whose coverage overlaps with the coverage of the sensor s^{curr}_{DM} will be treated as a candidate sensor of s^{next}_{DM}. Let $l^{max}_{s_i,s_j}$ denote the maximum defense length contributed by a pair of active sensors s_i and s_j if the two sensors participate in the defense barrier. The value of $l^{max}_{s_i,s_j}$ can be evaluated by Exp. (19)

$$l^{max}_{s_i,s_j} = \left(y_i - y_j\right) + \left(x_j - x_i\right) \cdot Max(W, L) \tag{19}$$

In Exp. (19), the multiplication of $Max(W, L)$ and $(x_j - x_i)$ emphasizes that the defense length should be increased in the horizontal direction since a straight defense barrier will use the minimum number of active sensors from left boundary to the right boundary.

The s^{curr}_{DM} will select one s_i from $S^{next}_{DM,candidate}$ as the s^{next}_{DM} if the $l^{max}_{s_i,s^{curr}_{DM}}$ has the maximal value. Then s^{curr}_{DM} will give the authorization to s^{next}_{DM} in the next round to choose the new sensor to participate in the defense barrier. This process will be repeated in every round to construct the new barrier segment until the constructed barrier reaches the right boundary. The s^{curr}_{DM} and s^{next}_{DM} in the last round will become new s^{pre}_{DM} and s^{curr}_{DM} in the current round, respectively. In each round, the sensor which plays the role of s^{curr}_{DM} will change the state from sleeping to active. Therefore, the set of sleeping sensors S^{sle} should be updated according to Exp. (20)

$$S^{sleep} = S^{sleep} \backslash \{s^{curr}_{DM}\} \tag{20}$$

Fig. 4(a) gives an example to illustrate the abovementioned process. As shown in Fig. 4(a), sensors s_1 and s_2 play the roles of s^{pre}_{DM} and s^{curr}_{DM}, respectively. Since sensor s_2 is the current *DM* and its sensing range overlaps with those of sensors s_3, s_4 and s_5, therefore we have

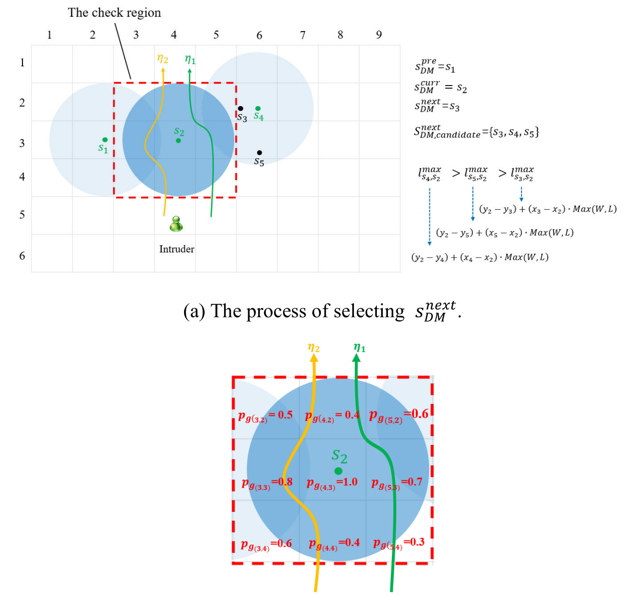
$$S^{next}_{DM,candidate} = \{s_3, s_4, s_5\}$$

The values of $l^{max}_{s_2,s_3}$, $l^{max}_{s_2,s_4}$ and $l^{max}_{s_2,s_5}$ can be calculated by applying Exp. (19). As a result, sensor s_4 has the maximal defense length value. Hence, sensor s_4 will be the best one to further play the role of s^{next}_{DM}.

If the $S^{next}_{DM,candidate} = \emptyset$, the s^{curr}_{DM} will give back the authorization to s^{pre}_{DM}. Then the s^{pre}_{DM} will play the role of s^{curr}_{DM} and again implement the same process to find other feasible s^{next}_{DM} from the updated $S^{next}_{DM,candidate}$.

2) TASK II. IDENTIFYING BOTTLENECK GRIDS

Recall that the s^{next}_{DM} has been selected in the barrier extending task. Since the sensing range of s^{next}_{DM} is overlapped with that of s^{curr}_{DM}, it implies that the cooperative sensing by s^{curr}_{DM} and s^{next}_{DM} will increase the surveillance quality of the sensing range of s^{curr}_{DM}. Let $\mathcal{A}^{check}_{curr}$ denote the sensing range of s^{curr}_{DM}, which needs to be further checked if the surveillance quality of the defense barrier to this region is qualified. This task aims to check the surveillance quality of $\mathcal{A}^{check}_{curr}$ and guarantee the quality of this region is qualified.



(a) The process of selecting s^{next}_{DM}.

(b) The sensing probability of each grid in $\mathcal{A}^{check}_{curr}$.

FIGURE 4. The process of selecting s^{next}_{DM} and the sensing probability of each grid in $\mathcal{A}^{check}_{curr}$.

Let $\mathfrak{p}^{check}$ denote the set of possible crossing paths passing through the check region $\mathcal{A}^{check}_{curr}$. Let η^{weak} denote the crossing path which has the weakest surveillance quality, as compared with all the possible crossing paths in $\mathfrak{p}^{check}$. That is

$$\eta^{weak} = \arg \min_{\eta \in \mathfrak{p}^{check}} q_\eta \tag{21}$$

Since the grids in $\mathcal{A}^{check}_{curr}$ are countable, the number of possible grid-based crossing path is limited and η^{weak} can be found. Let q^{weak} denote the surveillance quality of the crossing path η^{weak}. If q^{weak} does not satisfy the user predefined quality q_{req}, the grids that are passed through η^{weak} will become the bottleneck grids which could be improved.

The following further presents the mechanism for improving the surveillance quality of the defense barrier to the η^{weak} when it satisfies the condition $q^{weak} < q_{req}$. Let G_η denote the set of grids that are passed by η. It is obvious that G^{weak} is the set of grids which are passed by η^{weak}. As mentioned above, the surveillance quality of the barrier to a crossing path η^{weak} is calculated by the summation of sensing probability of the grids in G^{weak}. The derivation of q^{weak} is presented in Exp. (22).

$$q^{weak} = \sum\nolimits_{g_{(x,y)} \in G^{weak}} p\left(\Phi_{(x,y)}, g_{(x,y)}\right) \tag{22}$$

The problem of finding η^{weak} and computing q^{weak} is identical to the shortest path problem which can be solved by applying the Floyd-Washall algorithm [26]. The Floyd-Washall algorithm is used to find the summed weights of shortest paths between all the pairs of vertices in an edge-weighted directed graph.

As shown in Fig. 4(a), sensors s_1 and s_2 play the roles of s_{DM}^{pre} and s_{DM}^{curr}, respectively. There are two crossing paths η_1 and η_2. The check region $\mathcal{A}_{curr}^{check}$ is the sensing range of s_2, which has been marked with the red dotted line. The sensing probability of each grid in $\mathcal{A}_{curr}^{check}$ is given in the corresponding grid in Fig. 4(b). By applying the Floyd-Washall algorithm, we have the following three results:

$$\eta^{weak} = \eta_1,$$
$$G^{weak} = \{g_{(5,4)}, g_{(5,3)}, g_{(4,2)}\}, \quad \text{and } q^{weak} = 1.4.$$

Then the *GSMS* algorithm will verify if q^{weak} satisfies the required surveillance quality q_{req}. If $q^{weak} < q_{req}$, the *GSMS* algorithm will perform the operations in *Task I and Task II* in the next round to extend the barrier. Otherwise, the *GSMS* algorithm will perform the operations defined in *Task III* to further schedule more sensors for improving the surveillance quality of η^{weak}. The *Tasks II* and *Task III* will be repeatedly executed until all the crossing paths satisfy $q_\eta \geq q_{req}$ for all $\eta \in \mathfrak{p}^{check}$.

3) TASK III. SCHEDULING SENSOR FOR BOTTLENECK GRIDS

This task aims to schedule the sensors to participate in the barrier construction such that the surveillance quality q^{weak} of region $\mathcal{A}_{curr}^{check}$ to the weakest crossing path η^{weak} can satisfy the condition $q^{weak} \geq q_{req}$. Recall that G^{weak} denote the grids passed by the crossing path η^{weak}. These grids are called *bottleneck grids*. Let $S^{help} = \{s_1^h, s_2^h, \ldots, s_{|S^{help}|}^h\}$ denote the set of sleeping sensors whose sensing ranges overlap with the grids in G^{weak}. The s_{DM}^{curr} will compute the improved surveillance quality of each sensor $s_i^h \in S^{help}$ to G^{weak} if a new sensor s_i^h participates in the monitoring task. To minimize the number of new sensors, the *GSMS* algorithm prior schedules the sensor, say $s_j^h \in S^{help}$, which has the maximal contribution to G^{weak}. Let q_j^{weak} denote the weakest surveillance quality of defense barrier to region $\mathcal{A}_{curr}^{check}$ if a new sensor $s_j^h \in S^{help}$ participates in the monitoring task. Let c_j denote the contribution of sensor $s_j^h \in S^{help}$, the c_j can be calculated by applying Exp. (23)

$$c_j = q_j^{weak} - q^{weak} \tag{23}$$

Let s^{best} denote the sensor $s_j^h \in S^{help}$ that has the maximal contribution to G^{weak}. That is

$$s^{best} = \arg \max_{s_j^h \in S^{help}} c_j \tag{24}$$

It is possible that two or more sensors have identical contribution to G^{weak}. Let S^{best} denote the set of sensors which satisfy Exp. (24). The proposed *GSMS* algorithm expects that the selected s^{best} can cover all possible grids in $\mathcal{A}_{curr}^{check}$ such that s^{best} can not only improve the surveillance quality of grids in G^{weak} but also improve the surveillance quality

The *GSMS* Algorithm

Inputs:
1. A rectangle monitoring region R.
2. A set of sensors $S = \{s_1, s_2, \ldots, s_n\}$ randomly deployed in R.
3. The physical location (x_i, y_i) of each deployed sensor s_i, where $s_i \in S$
4. The predefined required surveillance quality q_{req}

Outputs: A set of active sensors which construct the barrier aiming at minimizing the number of active sensors and guaranteeing the surveillance quality.

Space Partitioning Phase

Step 1. /* ***Space Partitioning*** */
Partition the monitoring region R into $c_1 \times c_2$ equal-sized grids;

Sensing Probability Calculation Phase

Step 2. /* ***Sensing Probability Calculation*** */
If the grid $g_{(x,y)}$ is fully covered by one sensor s_i
Calculates $p(s_i, g_{(x,y)})$ according to Exp. (14)
else if the grid $g_{(x,y)}$ is partially covered by one sensor s_i
Calculates $p(s_i, g_{(x,y)})$ according to Exp. (16)
else if $g_{(x,y)}$ is covered by the set of sensors $\Phi_{(x,y)}$
Calculates $p(\Phi_{(x,y)}, g_{(x,y)})$ according to Exp. (17)
End

Scheduling and Barrier Construction Phase

Step 3. /****Barrier Extending****/
$S_{candidate}^{first} = \emptyset$
For (each sensor $s_i \in S$) {
If (s_i locate in the most upper left position of R $\|\mathcal{A}_{s_i} \cap W_{left} \neq \emptyset$)
$s_{first} = s_i$
End
$s_{DM}^{curr} = s_{first}$
Repeat {
For (each sensor $s_i \in S_{DM,candidate}^{next}$) {
Calculates $l_{s_{DM}^{curr}, s_i}^{max}$ according to Exp. (19)
If ($s_i = \arg max\, l_{s_{DM}^{curr}, i}^{max}$)
$s_{DM}^{next} = s_i$ }
If ($S_{DM,candidate}^{next} = \emptyset$)
Apply the backtracking mechanism
End

Step 4. /* ***Identifying Bottleneck Grids****/
Calculates the q^{weak} by applying Floyd-Washall algorithm
If $q^{weak} \geq q_{req}$
Continue
else if $q^{weak} < q_{req}$

Step 5. /* ***Scheduling Sensor for Bottleneck Grids*** */
Repeat {$S^{best} = \emptyset$
For (each sensor $s_i^h \in S^{help}$){
Calculates the contribution c_i according to Exp. (23)
If (sensor s_j^h satisfy $s_j^h = arg \max_{s_j^h \in S^{help}} c_i$)
$S^{best} = S^{best} \cup \{s_j^h\}$
End
If ($|S^{best}| = 1$)
$s^{best} = s_j$
else if ($|S^{best}| > 1$)
For (each sensor $s_k \in S^{best}$) {
If s_k does not satisfy Exp. (26)
$S^{best} = S^{best} \backslash s_j$ }
If ($|S^{best}| > 1$)
Let s^{best} be the sensor which is located closest to the top boundary
End
$S^{sle} = S^{sle} \backslash \{s^{best}\}$
Recalculate q_i^{weak} by applying Floyd Washall algorithm}
Until $q^{weak} \geq q_{req}$
}
}
Until $\mathcal{A}_{s_{DM}^{curr}} \cap W_{right} \neq \emptyset$ }

FIGURE 5. The process of the *GSMS* algorithm.

of other grid-based crossing paths in $\mathcal{A}_{curr}^{check}$. Consequently, the sensor that satisfies Exp. (25) will be selected.

$$s^{best} = \arg \max_{s_k \in S^{best}} count(g_{(x,y)} \in \mathcal{A}_{curr}^{check}) \quad (25)$$

where $count()$ is a function which counts the number of grids $g_{(x,y)} \in \mathcal{A}_{curr}^{check}$ that can be covered by s_k. If Exp. (25) still cannot uniquely select the s^{best}, the sensor which is located closest to the top boundary will be finally selected to play the role of s^{best} since the proposed *GSMS* algorithm aims to fully utilize the sensors from top to bottom.

Recall that S^{sleep} denotes the set of unscheduled sensors. When the s^{best} has been determined, it should be removed from the set S^{sleep}. That is,

$$S^{sleep} = S^{sleep} \backslash \{s^{best}\} \quad (26)$$

Then the η^{weak} should be updated and the q^{weak} should be recalculated by performing *Task II* and *Task III* until the new weakest surveillance quality q^{weak} is larger than q_{req}. The abovementioned process will be executed repeatedly until all crossing paths satisfy $q_\eta \geq q_{req}$ for all $\eta \in \mathfrak{p}^{check}$.

Fig. 5 summaries the process designed in *GSMS* algorithm. Steps 1 and 2 summarize the space partitioned phase and the sensing probability calculation phase, respectively. Finally, Steps 3, 4 and 5 summarize the scheduling and barrier construction phase.

The performance evaluation, in terms of the number of active sensors, the lifetime of the WSNs, the efficiency of barrier construction as well as the cooperative sensing probability, will be further investigated.

V. SIMULATION

This section studies the performance evaluation of the proposed *GSMS* algorithm against the existing Branch Mechanism (*BRA*) [18] and Best Fit Coverage Approach (*BCA*) [20]. The *BRA* aimed to find the maximum disjoint sets of sensors to form the barrier with k-coverage. The *BCA* firstly constructed a CA-Net. Then it constructed barrier based on the CA-Net. It aimed to construct a maximum number of k-barrier each of which consistsing of the minimum number of sensors. Both *BRA* and *BCA*are decentralized approaches and are designed based on the grid-based method. According to the comparison shown in Table. 1, the two algorithms are the most comparable with the proposed *GSMS* algorithm. The following firstly illustrates the simulation environment. Then the simulation results are presented.

A. SIMULATION ENVIRONMENT

The simulation parameters are given in Table 2. The sensor nodes are randomly deployed in the monitoring area as shown in Fig. 6. The size of the monitoring region is $800m \times 400m$ while the number of deployed sensors is ranging from 200 to 400. The sensing and communication radiuses of each sensor are set at 25m and 50m, respectively. The grid size is set at $5m \times 5m$.

TABLE 2. Simulation parameter.

Parameter	Value
Simulator	Matlab
Monitoring Region	800m×400m
Number of Sensors	200-400
Sensing Radius	25m
Communication Radius	50m
Grid Size	5m×5m
Deployment	Randomly / Uniformly

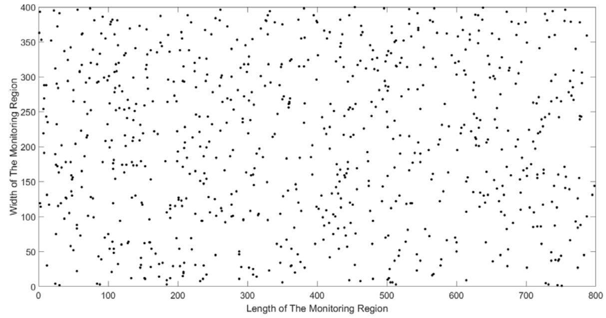


FIGURE 6. A scenario that sensors are randomly deployed in a monitoring area with size 800m*400m.

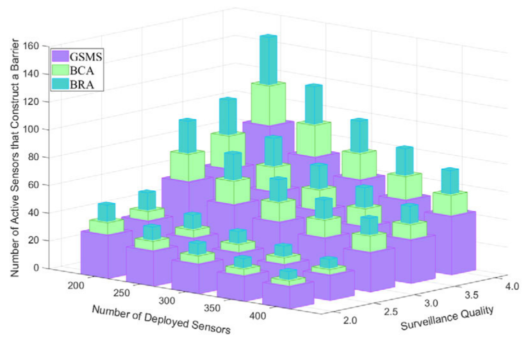


FIGURE 7. Comparison of the number of active sensors required for constructing a qualified barrier by varying the number of deployed sensor and the required surveillance quality.

B. SIMULATION RESULT

Fig. 7 compares the number of active sensors required for constructing a qualified barrier by varying the number of deployed sensors and the required surveillance quality. In general, three compared algorithms have the similar trend that the number of required active sensors is decreased with the number of deployed sensors. This occurs because that a large number of deployed sensors provide more opportunities to find the appropriate sensors which contribute better surveillance quality for the constructed barrier. As a result, fewer sensors are selected to support the required surveillance quality when the number of deployed sensors grows. In general, the proposed *GSMS* algorithm outperforms existing *BRA* and *BCA* algorithms. One reason is that the proposed *GSMS* algorithm accurately estimates the surveillance quality since the probabilistic sensing model is applied. In addition, the proposed *GSMS* algorithm selects the sensor with the largest contribution to increase the surveil-

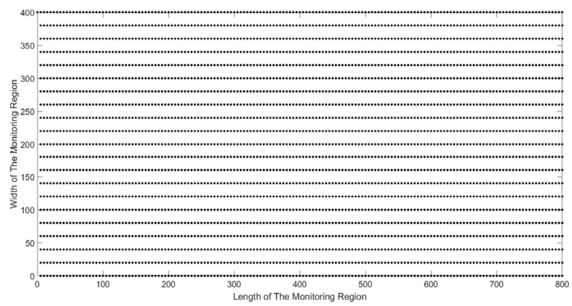


FIGURE 8. An example of deployment that the uniform deployment strategy is applied in a monitoring region with size 800m∗400m.

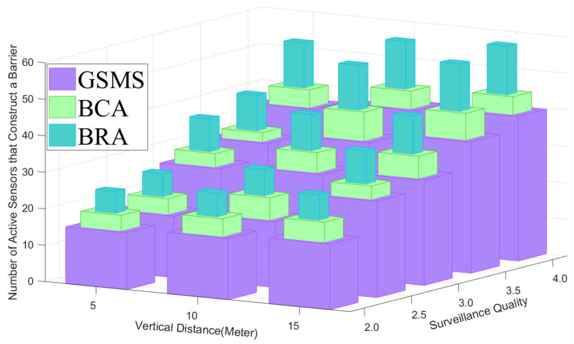


FIGURE 9. Comparison of the number of active sensors required for constructing a qualified barrier by varying the number of deployed sensor and the distance between two rows.

lance quality of bottleneck grids. Hence the number of required active sensors can be reduced, as compared with the other two algorithms. Furthermore, the existing *BRA* and *BCA* algorithms construct the barrier based on the continuous cover set. In case that the required quality is not satisfied in a small area, the two algorithms might wake up a set of sensors to globally increase one or more coverages for the whole barrier. However, the proposed *GSMS* only needs to wake up a few number of sensors to locally improve the required surveillance quality. As a result, the proposed *GSMS* achieves better performance than the compared two algorithms.

In addition to the random deployment, Fig. 8 shows the example that the uniform deployment strategy is applied. Fig. 9 compares the number of active sensors required for constructing a qualified barrier by varying the distance between two rows and the required surveillance quality. The required surveillance quality is varied ranging from 2.0 to 4.0 while the distance between two contiguous rows is varied ranging from 5 to 15 meters. In general, the number of sensors required to construct a barrier is increased with the distance between two rows. This occurs because larger distance will reduce the contribution of the newly scheduled sensor to the surveillance quality. The performance of the proposed *GSMS* algorithm is better than those of *BCA* and *BRA* algorithms in all the cases. This occurs because that the surveillance quality is accurately estimated by the proposed *GSMS*. Besides, the proposed *GSMS* prior schedules the sensor with the largest contribution to improve the monitoring quality of the weakest grids.

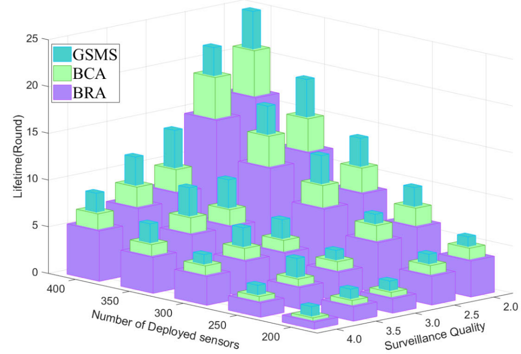


FIGURE 10. Comparison of *GSMS*, *BRA* and *BCA* in terms of the lifetime by varying the number of deployed sensors and the required surveillance quality.

Fig. 10 investigates the lifetime of the WSNs by varying the number of deployed sensors and the required surveillance quality. In general, the three compared algorithms have the common trend that the lifetime is increased with the number of deployed sensors and is decreased with the required surveillance quality. The proposed *GSMS* algorithm outperforms the compared *BCA* and *BRA* algorithms in most cases. This occurs because that *GSMS* selects the next decision maker s_{DM}^{next} from left to right and from top to down, aiming to utilize all sensors. As a result, the utilization of the deployed sensors can be increased. Another reason is that the barrier constructed by the proposed *GSMS* algorithm consists of smaller number of sensors.

Let notations q_{supp} and N_{requ} denote the surveillance quality and the number of sensors required for constructing a qualified barrier, respectively. The efficiency of an algorithm ζ, denoted by notation u_ζ, is defined by Exp. (27).

$$u_\zeta = \frac{q_{supp}}{N_{requ}} \tag{27}$$

Fig. 11 compares the efficiency of three compared algorithms by varying the number of deployed sensors and the required surveillance quality. As shown in Fig. 11, the efficiency of the three algorithms are generally increased with the number of deployed sensors. However, the efficiency is increased with the required surveillance quality before 3.0 but decreased with the required surveillance quality after 3.0. This occurs because that when the surveillance quality of barrier is larger than 3.0, the sensing probability of each grid almost achieves the maximum value. This reduces the contribution of the newly added sensor in terms of surveillance quality. The performance of the proposed *GSMS* algorithm is better than those of the compared *BRA* and *BCA* algorithms in most cases. This occurs because that *GSMS* identifies the bottleneck grids and improves the surveillance quality by waking up those sensors which have the maximal contributions to the grids. In addition, the proposed *GSMS* further considers the sensing frequency which accurately evaluates the

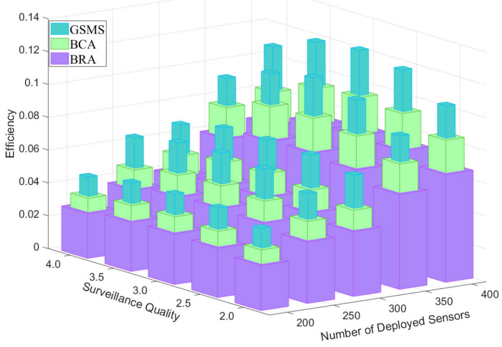


FIGURE 11. Comparison of *GSMS,BCA* and *BRA*in terms of the efficiency by varying the number of deployed sensors and the required surveillance quality.

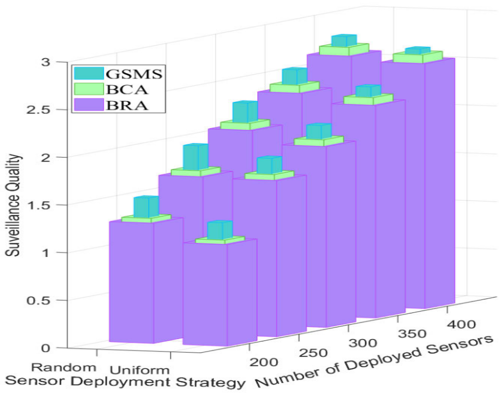
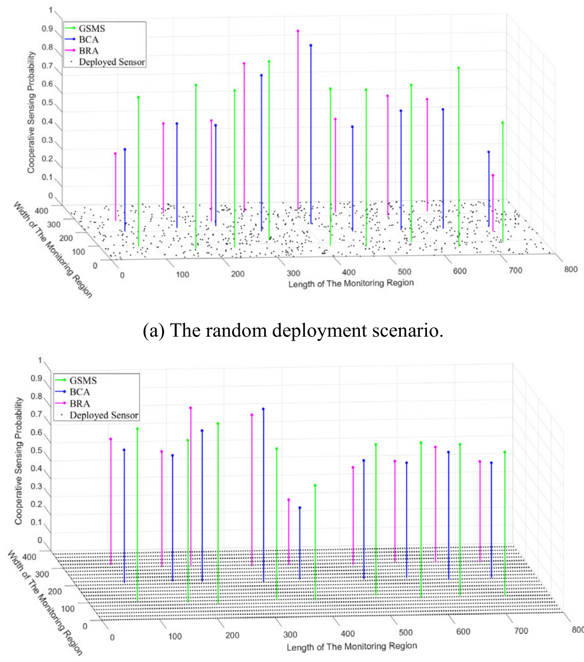


FIGURE 12. Surveillance quality comparison by applying different deployment strategies and varying the number of deployed sensors.

surveillance quality of the constructed barrier. Therefore, the number of sensors selected for constructing the barrier can be significantly reduced, increasing the efficiency of the proposed *GSMS*.

Fig. 12 further studies the impact of the random and uniform deployments on the surveillance quality. The number of deployed sensors is ranging from 200 to 400. To compare the surveillance qualities of the three algorithms, this experiment does not consider the required surveillance quality q_{req}. Instead, the compared three algorithms aim to construct a 2-coverage barrier. As shown in Fig. 12, the surveillance qualities of the three compared algorithms have two common trends. The first one is that the surveillance quality is increased with the number of deployed sensors. This occurs because that a large number of sensors can help select the sensor with larger contribution. The second trend is that the uniform deployment strategy obtains a better result than the random deployment strategy. This occurs because that uniform deployment strategy provides more balanced surveillance qualities. Therefore, each sensor almost has contribution in terms of the surveillance quality, as compared with the random deployment. In comparison, the proposed *GSMS* outperforms the other two algorithms in all cases. This occurs because that *GSMS* considers the contribution



(a) The random deployment scenario.

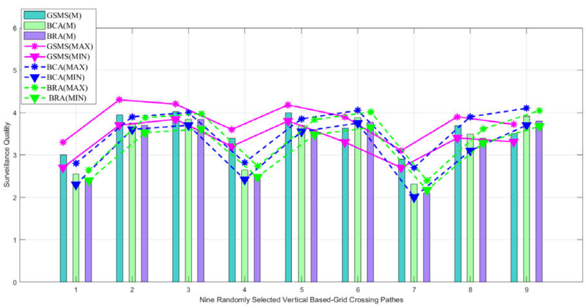
(b) The uniform deployment scenario.

FIGURE 13. Comparison of *GSMS, BCA* and *BRA* in terms of the cooperative sensing probability of randomly selected 9 points.

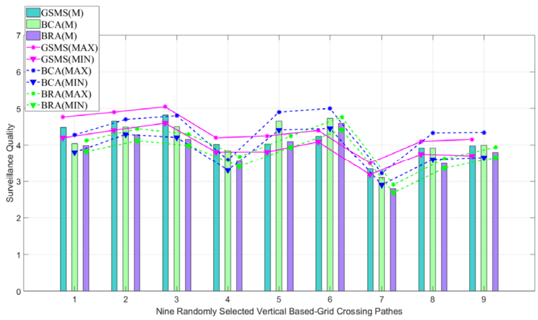
of each sensor and selects the sensor with maximal contribution to improve the surveillance quality of the bottleneck grids.

Fig. 13 investigates the cooperative sensing probability of randomly selected 9 points by applying the *GSMS*, *BCA* and *BRA* algorithms. In the experiment, the number of deployed sensors is set at 400. The required coverage degree is two. Based on this requirement, three barriers are constructed by applying the compared *GSMS*, *BCA*, and *BRA*. Then the experiment arbitrarily constructs 9 straight lines as the crossing paths which pass through the three barriers. As a result, there are 9 intersection points on each barrier. For each intersection point, the experiment calculates the cooperative sensing probability of those sensors that can cover that point. Fig. 13(a) depicts the results of cooperative sensing probabilities of the intersection points. In comparison, the *GSMS* outperforms *BCA* and *BRA* in terms of cooperative sensing probability in most cases. The cooperative sensing probability of each intersection point can be treated as the cooperative contribution of those sensors that can cover that point. Since *GSMS* schedules fewer sensors to satisfy the required surveillance quality, the cooperative contribution of each point detected by the active sensors which are scheduled by *GSMS* algorithm is larger than that of *BCA* and *BRA*. Fig. 13(b) also depicts a similar result as shown in Fig. 13(a) though it adopts uniform deployment strategy.

Fig. 14 further investigates the surveillance qualities of *GSMS*, *BCA* and *BRA* algorithms by randomly constructing 9 vertical crossing paths. The parameter settings of the simulation environment are similar to those of Fig. 13.



(a) The constructed barrier is 2-coverage.



(b) The constructed barrier is 4-coverage.

FIGURE 14. Surveillance quality of constructed barrier to the 9 randomly selected vertical crossing paths by applying *GSMS*, *BCA* and *BRA* algorithms.

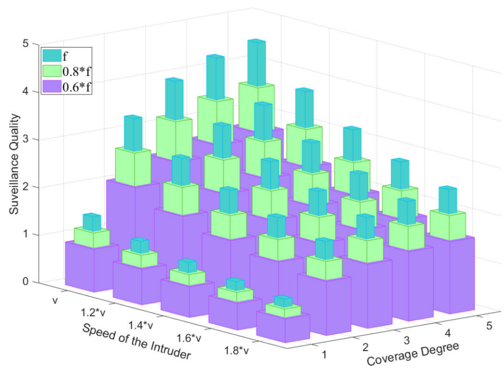


FIGURE 15. Comparison of different scanning frequencies by applying the *GSMS* algorithm by varying the speed of intruder and the coverage degree.

The deployment strategy applied in Figs. 14(a) and 14(b) is random deployment. In this experiment, the required surveillance quality is not considered. Instead, Fig. 14(a) aims to construct a 2-coverage barrier while Fig. 14(b) aims to construct a 4-coverage barrier. Let $A(M)$, $A(MAX)$ and $A(MIN)$ denote the mean, maximum and minimum values of surveillance quality of the constructed barrier by applying algorithm A, where A can be *GSMS*, *BCA* or *BRA*. As shown in Figs. 14(a) and 14(b), the surveillance quality of the barrier constructed by applying *GSMS* algorithm is better than those by applying *BCA* and *BRA* algorithms in most cases. This occurs because that the proposed *GSMS* accurately evaluates the sensing probability and selects the sensor with the largest contribution when constructing the defense barrier.

Fig. 15 further compares the surveillance quality by applying three different scanning frequencies of each active sensor. The scanning frequencies of each active sensor is controlled by either f, $0.8f$ or $0.6f$, where f denotes the basic frequency which guarantees that the intruder can be detected at least once. The intruder speed is ranging from 5m/s to 10m/s while the required surveillance quality is ranging from 1-coverage to 5-coverage. As shown in Fig. 15, the higher the scanning frequency is, the better the surveillance quality achieves. The experimental result shows that the surveillance quality is decreased with the intruder speed but is increased with the number of sensors. This occurs because that the high scanning frequency can detect the intruder many times in a fixed time period, which increases the surveillance quality. However, the intruder moving with a high speed will result in smaller detection opportunity and hence the surveillance quality is accordingly reduced.

VI. CONCLUSION

This paper proposed a decentralized barrier coverage mechanism *GSMS* which aims to construct a barrier using the minimal number of active sensors but guaranteeing the user defined surveillance quality in a decentralized manner. The proposed *GSMS* algorithm applies the probabilistic sensing model which accurately evaluates the sensing contribution of each sensor. The *GSMS* algorithm firstly partitions the monitoring region into several equal-sized grids for reducing the computing complexity. Then the sensing probability of each grid detected by sensors is calculated based on PSM. After that, the proposed *GSMS* identifies the bottleneck grids and prior schedules the sensor with the maximal contribution to the bottleneck grids. Simulation experiments shows that the proposed *GSMS* algorithm outperforms existing *BCA* and *BRA* algorithms in terms of the number of active sensors required for constructing a qualified barrier, the lifetime of the WSNs, the efficiency as well as the cooperative sensing probability. The future work will consider the rechargeable sensors and the sleep-wake up scheduling mechanism in order to achieve the perpetual lifetime of the WSNs.

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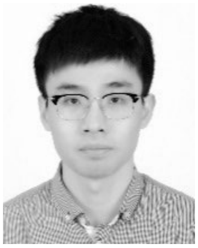

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